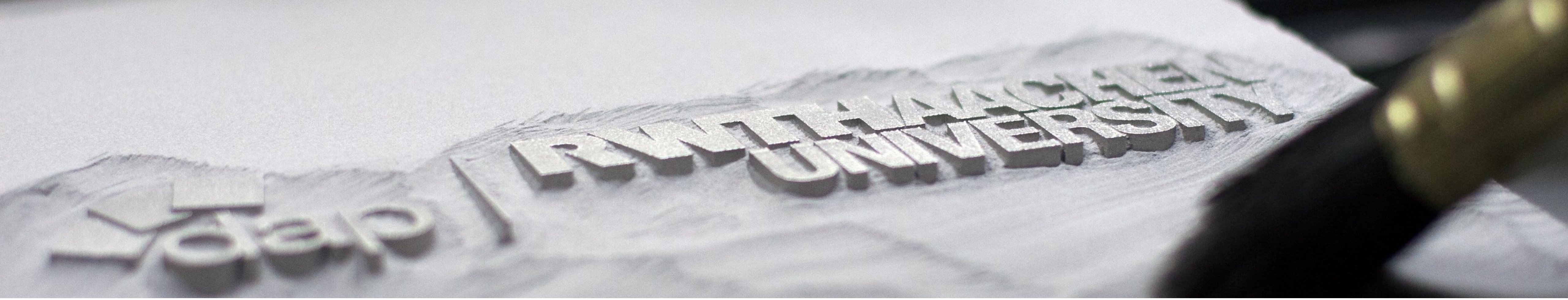

Variant flexible Hairpin Stator Production through Parametric Modeling and Additive Tooling

Presented by Carsten Putz, M.Sc., at MAMC 2022
Research Associate

Chair of Digital Additive Production
RWTH Aachen University
Campus-Boulevard 73
D-52074 Aachen

Publicly funded by:
Ministerium für Wirtschaft, Innovation, Digitalisierung und Energie des Landes Nordrhein-Westfalen

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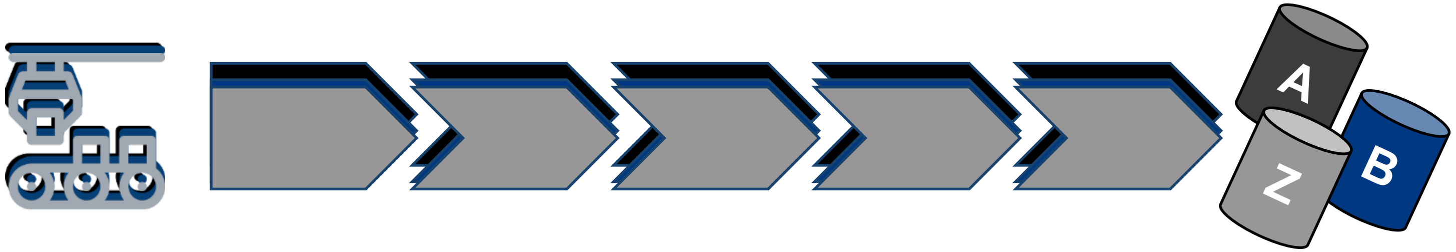
Motivation

Necessity of variant flexible production lines for electric traction drives

- "The increasing growth in the number of product variants poses a challenge to all areas of the company. In the context of production, this means primarily finding an optimal flexibility of the production systems used."

- With short development and life cycles of products, inflexible production results in
  - high investment costs
  - low quantities
  - low to no economies of scale

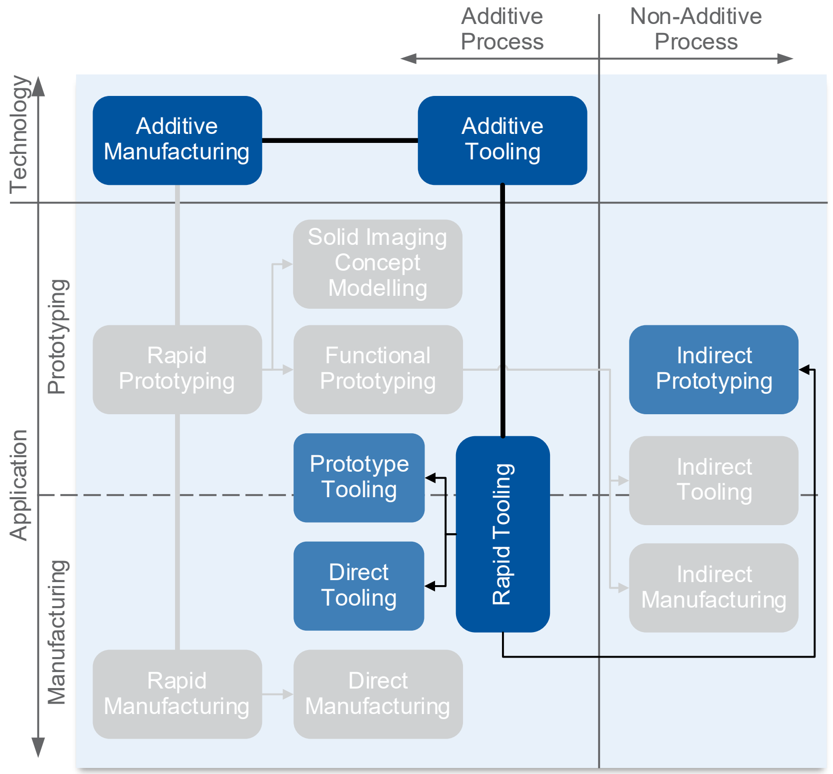
Variant flexible design of production process chains respectively their tools and devices

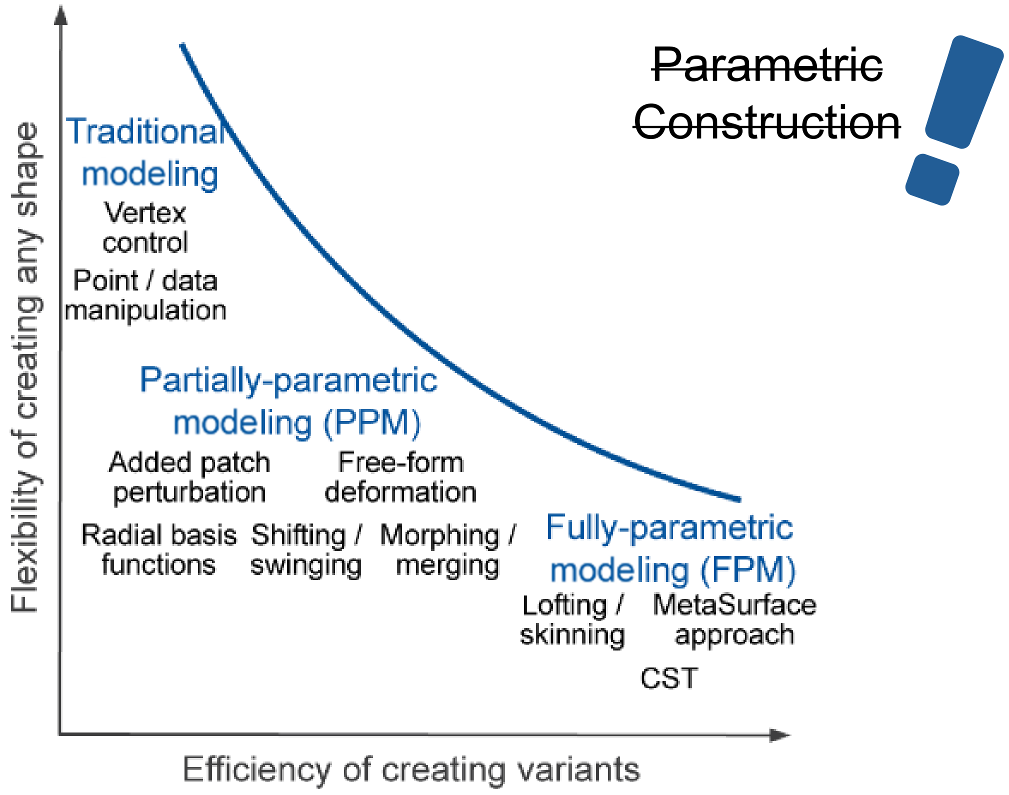


- high investment costs
- **large quantities**
- **economies of scale**

[1]

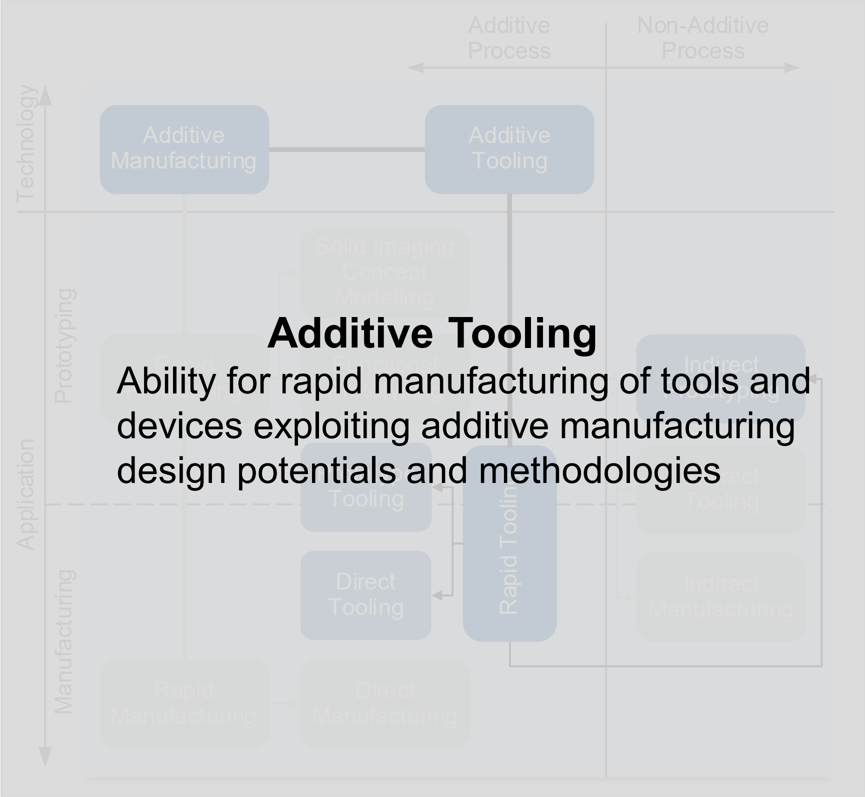
Additive Manufacturing
Key technology to achieve required innovations





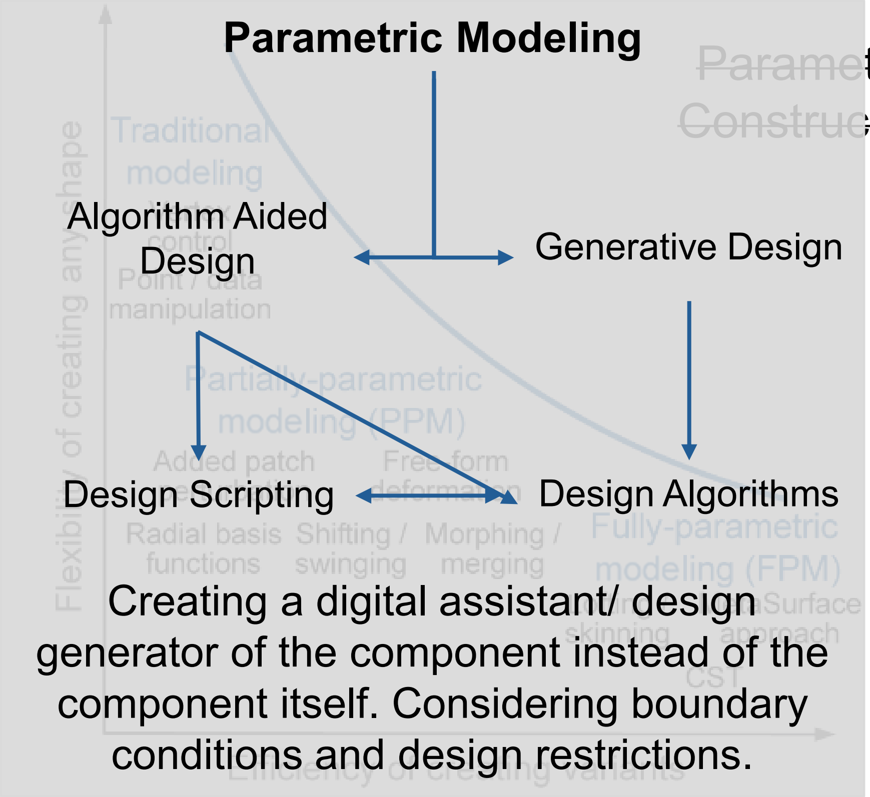
[2, 3]

Additive Manufacturing
Key technology to achieve required innovations



Additive Tooling

Ability for rapid manufacturing of tools and devices exploiting additive manufacturing design potentials and methodologies



Creating a digital assistant/ design generator of the component instead of the component itself. Considering boundary conditions and design restrictions.

~~Parametric Construction~~

Combination of additive tooling and parametric modeling as an approach to integrate variant flexibility into production lines

[2, 3]

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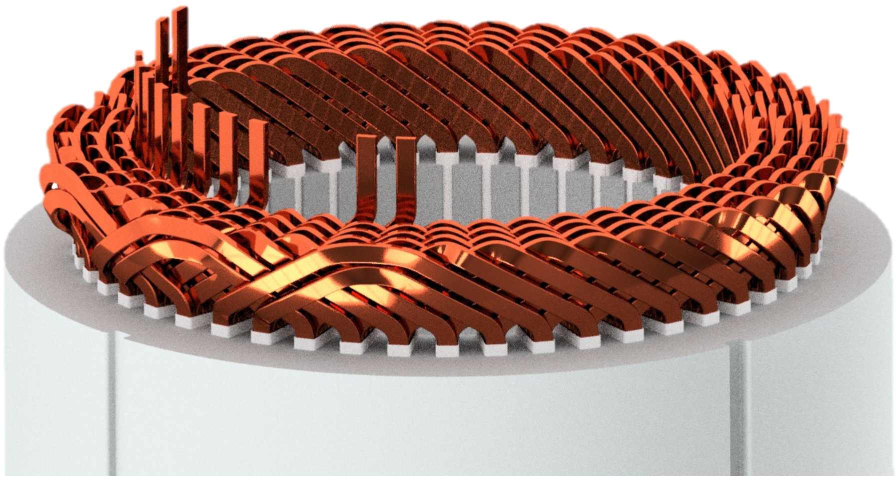
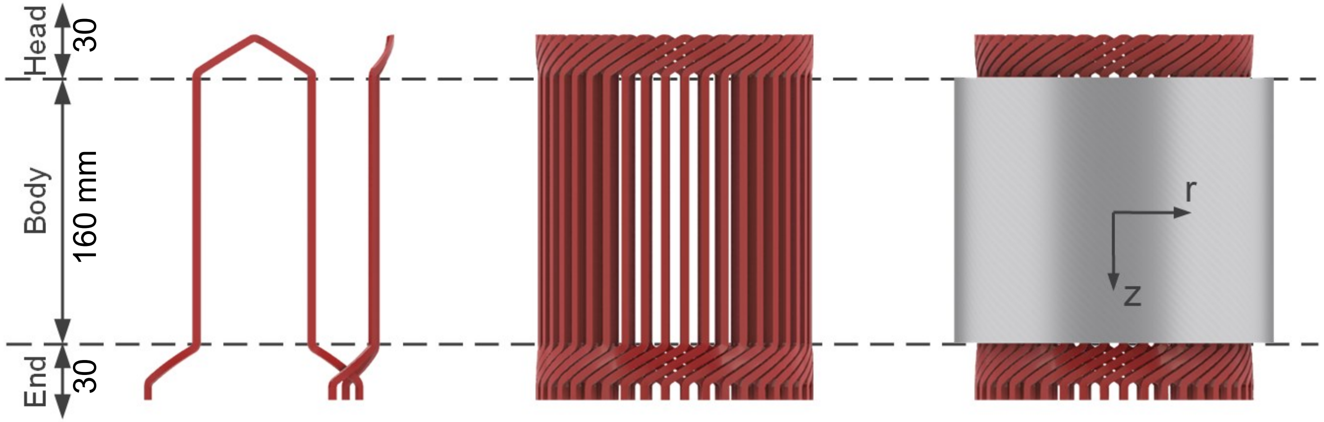
Hairpin Technology
Rectangular copper wire winding in stators of electric machines

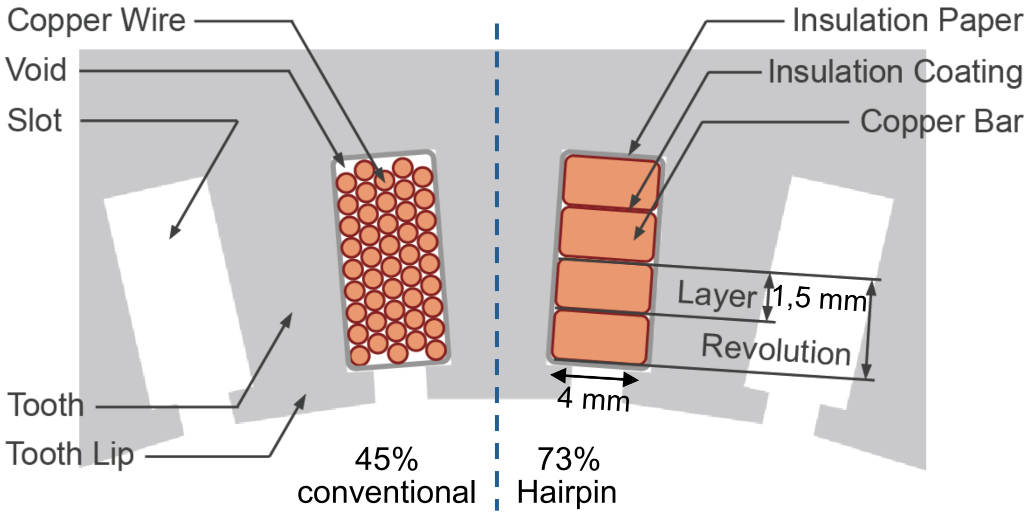
- Stator: stationary part of an e-machine
- Includes the copper coils which create the rotating magnetic field
- Hairpin: flat copper wire with rectangular cross section

$$R_{el}(T) = \frac{l}{A} * \frac{\sigma_{T_0}}{1+\alpha(T-T_0)}$$

→ higher copper fill factor: 73%
→ higher power density, less DC copper losses
→ deterministic production process behavior with higher level of automation







[4, 5]

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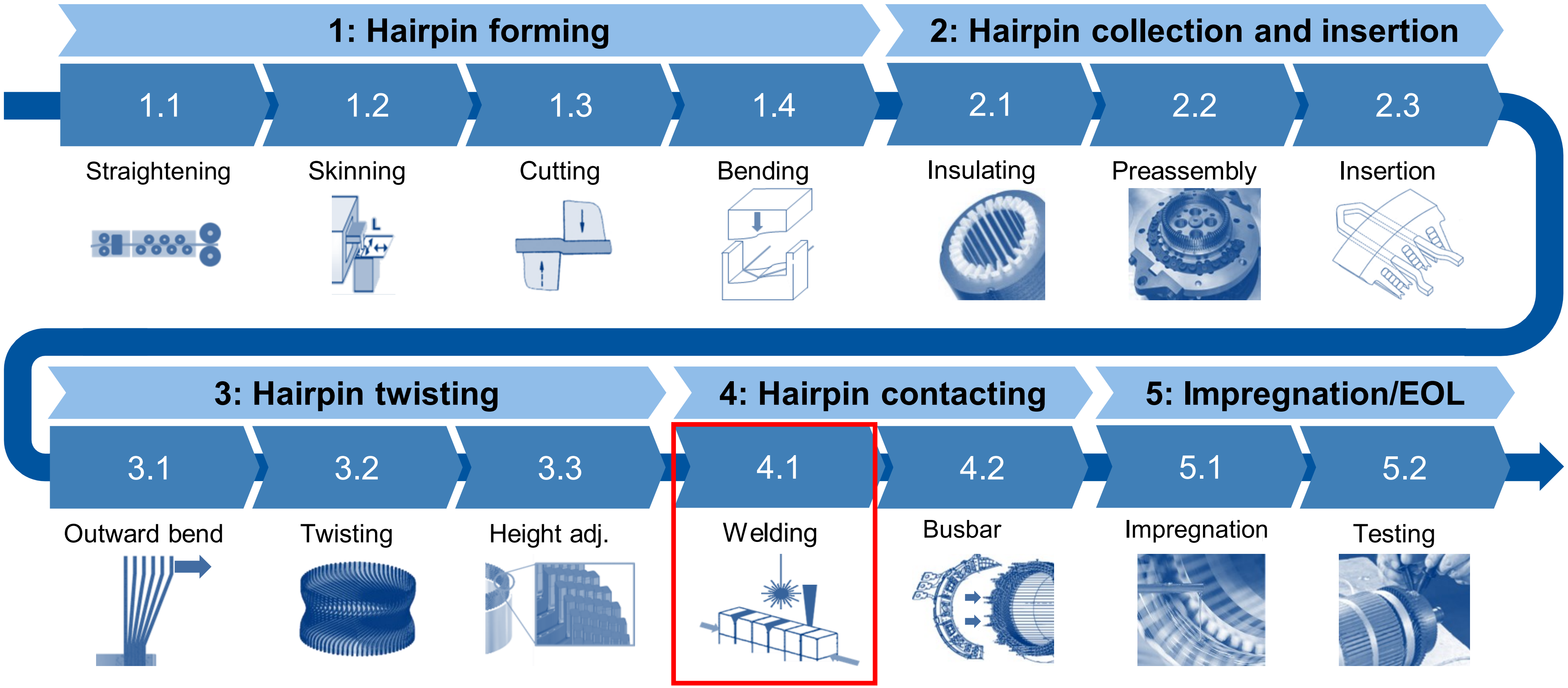
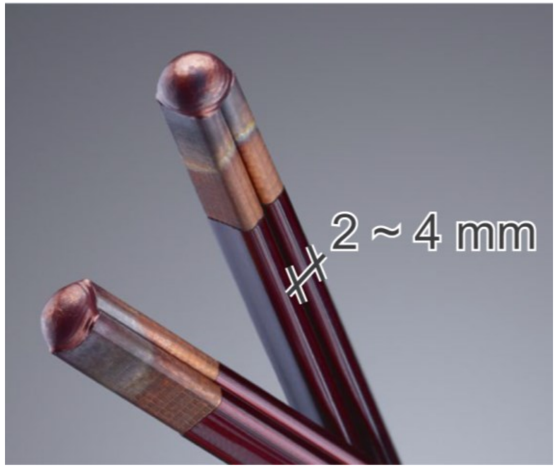
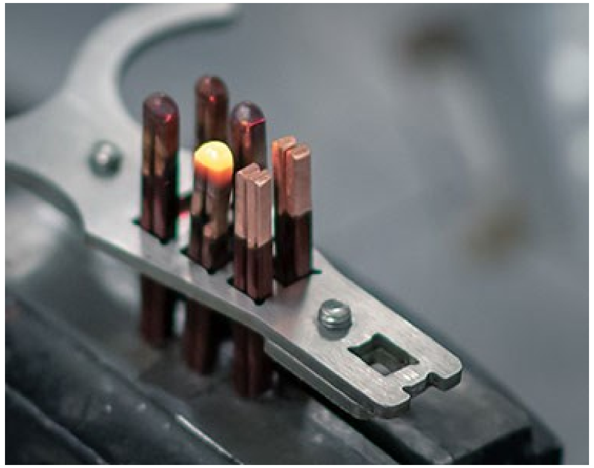
Hairpin Technology
Production process chain of hairpin stators

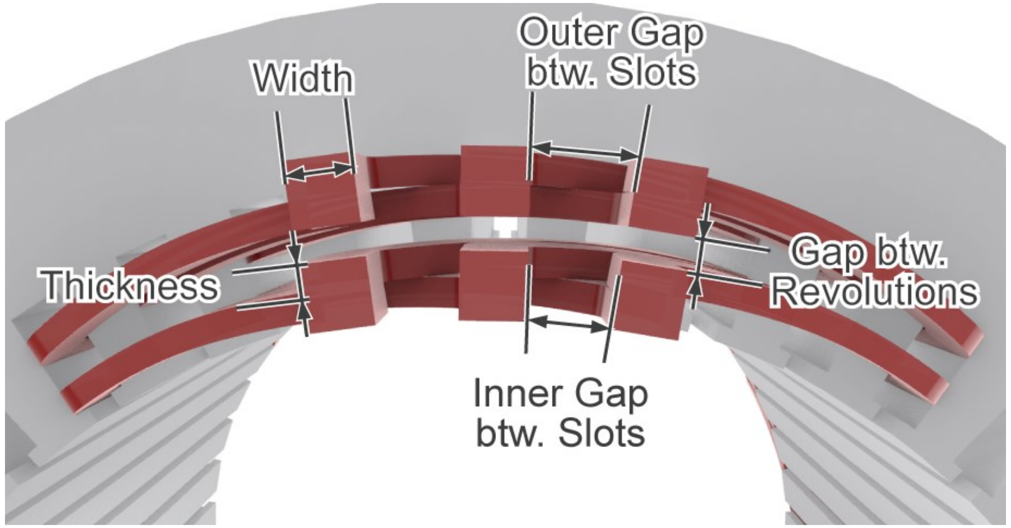


[5]

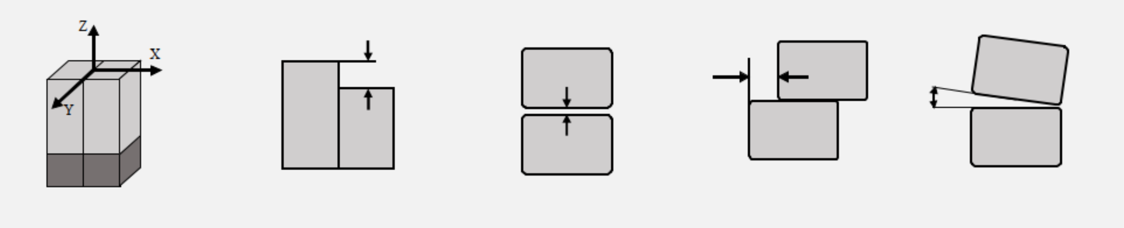
Hairpin Technology
Welding process step and its tool requirements







- Main function: creating welding joints of neighboring hairpin ends (in radial direction)
- Subfunctions
  - protection of welding splatters
  - handle tolerances of previous process step
  - resist temperature while laser welding
  - clamp several hairpin ends at once

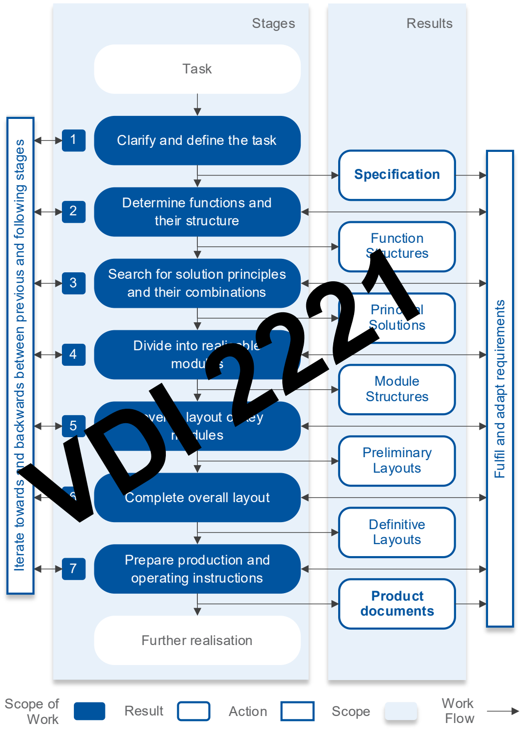


	Z-Deviation	Gap	Y-Deviation	Rotation by Z
Actual	max. 2,2 mm	max. 0,25 mm	max. 0,95 mm	max. 0,25 mm
Target	max. 1,1 mm	max. 0,1 mm	max. 0,5 mm	max. 0,1 mm

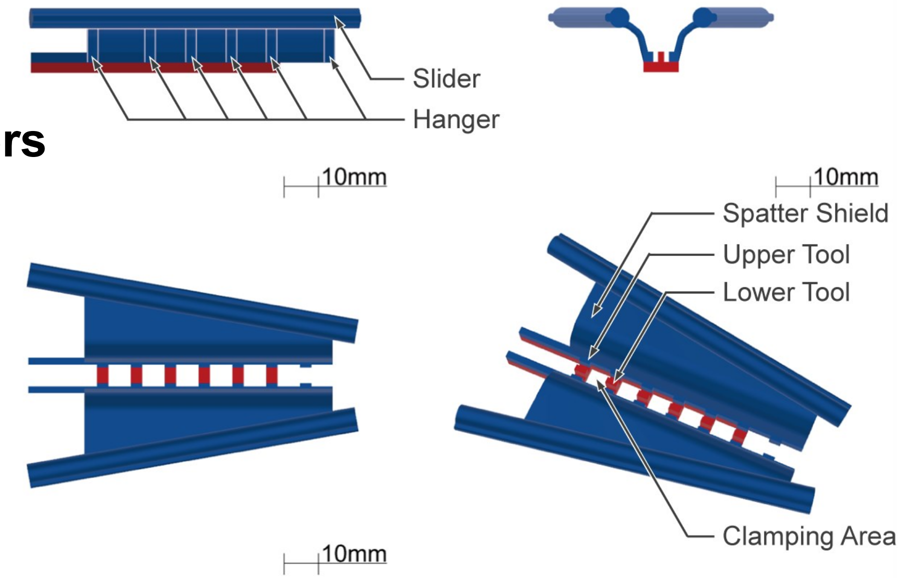
State of the art tools for hairpin clamping are dedicated to a **single product design**

[7, 8, 9]

Tool Concept Development
Focus on variant flexibility



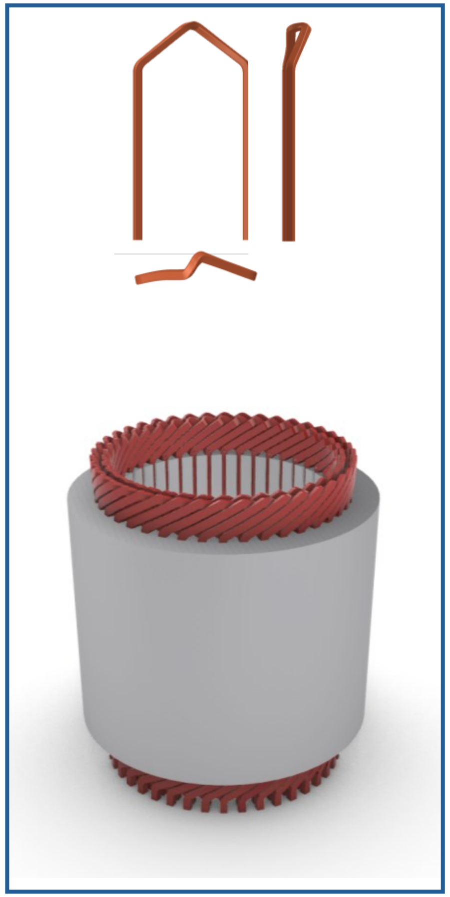
- Clamp hairpin ends for welding
- **Adapt variant flexible product parameters**
  - Stator diameter
  - Stator length
  - Number of slots
  - Number of hairpins per slot
  - Wire width
  - Wire depth
  - …
- Taking advantage of AM design potentials
- Suitable for LPBF production

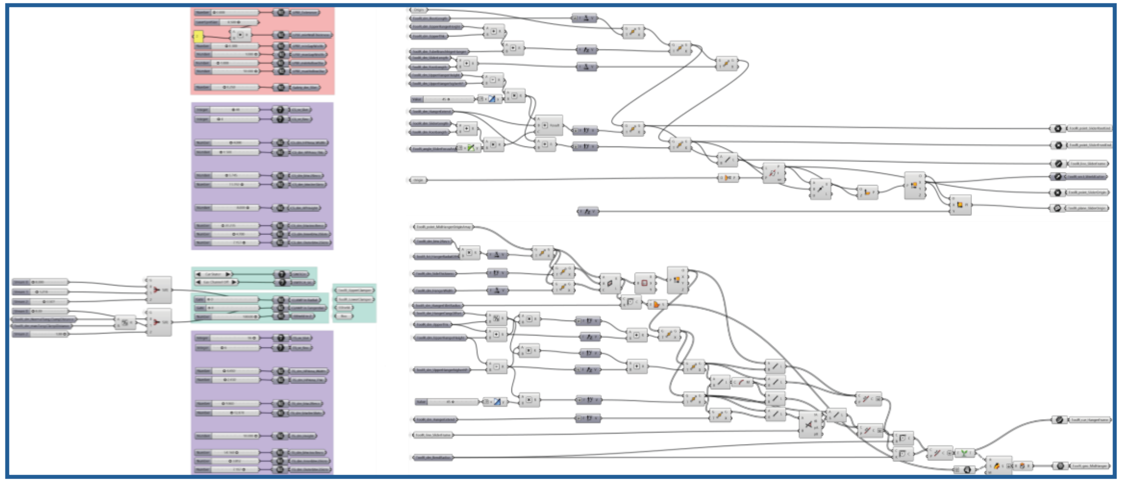


→ Trade off between a flexible tool considering all variable parameters and productivity

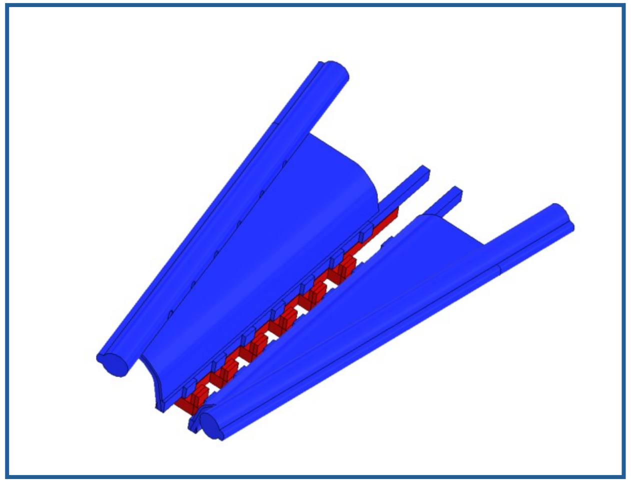
Need for automatic design adjustments of the tool in consideration of changing product parameters

Parametric Modeling
Implementing design algorithms for automatic design generation





Design script implementation in Grasshopper ® plugin of Rhinoceros3D®



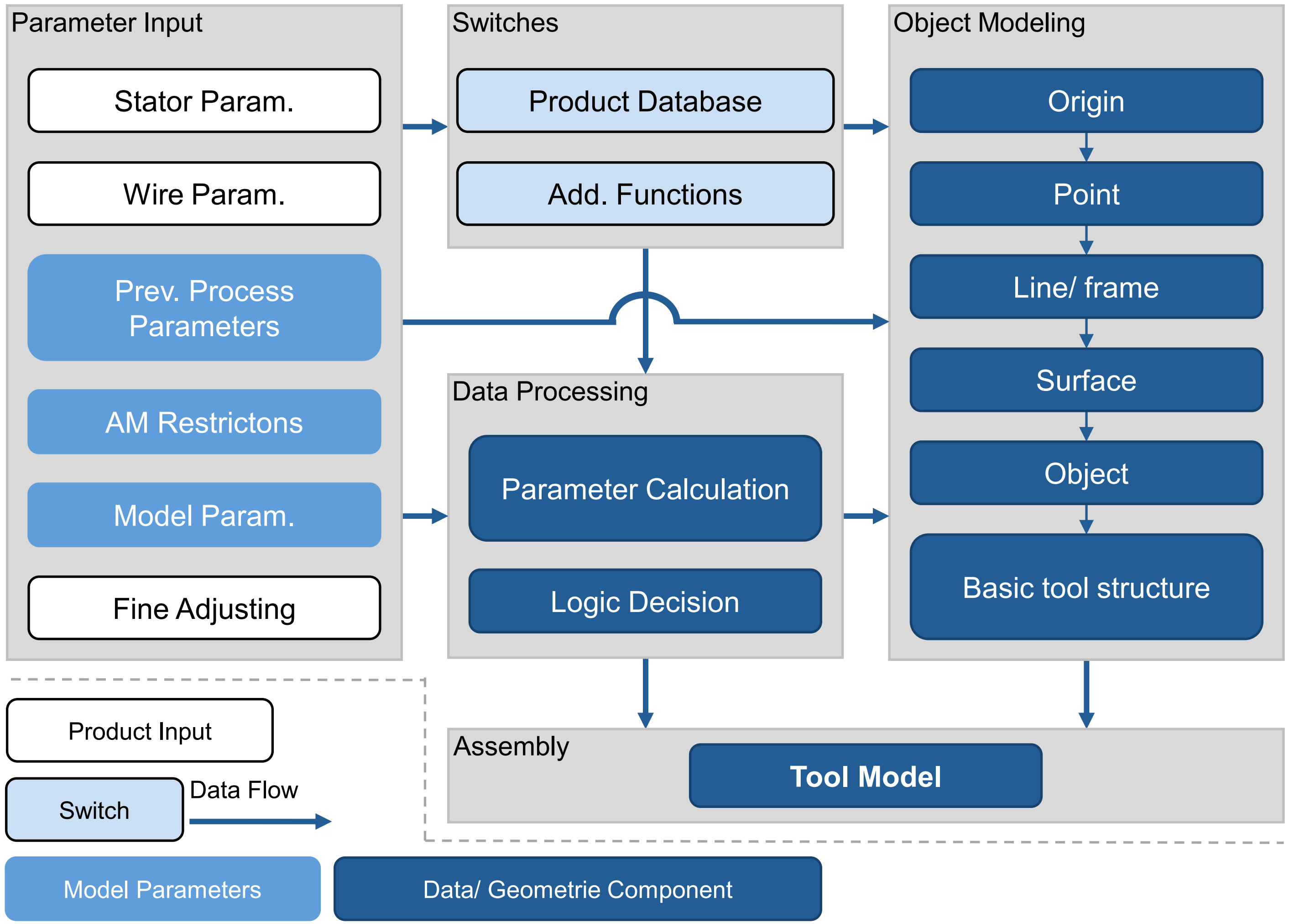
Data export to .step, .stl., etc.

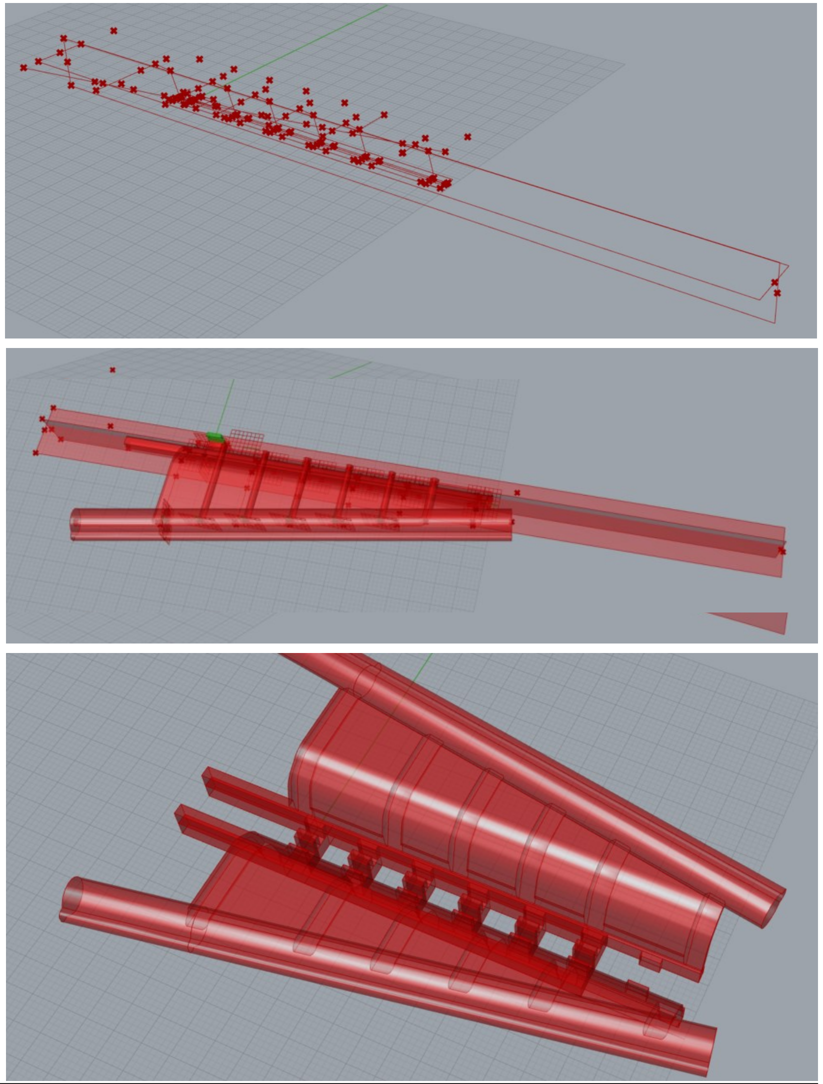
Input: Product Parameters

Design Algorithm

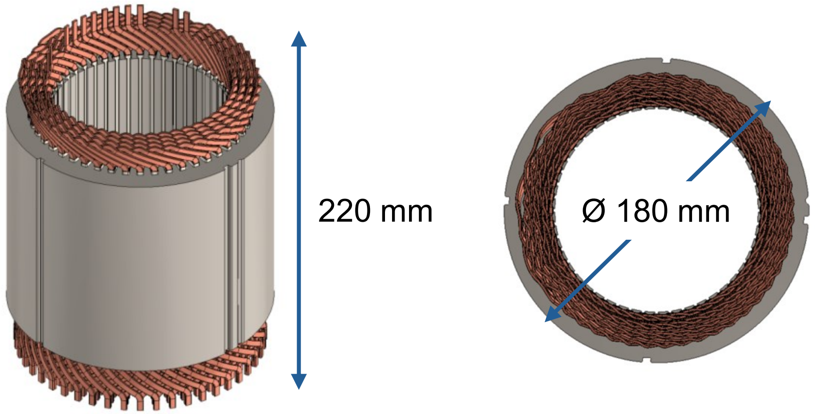
Tool Design

Parametric Modeling
Implementing design algorithms for automatic design generation

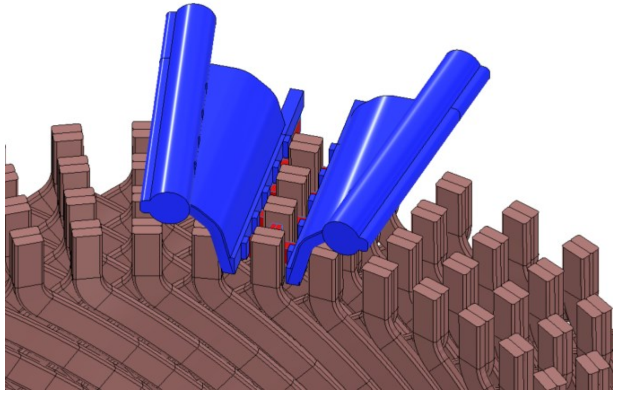


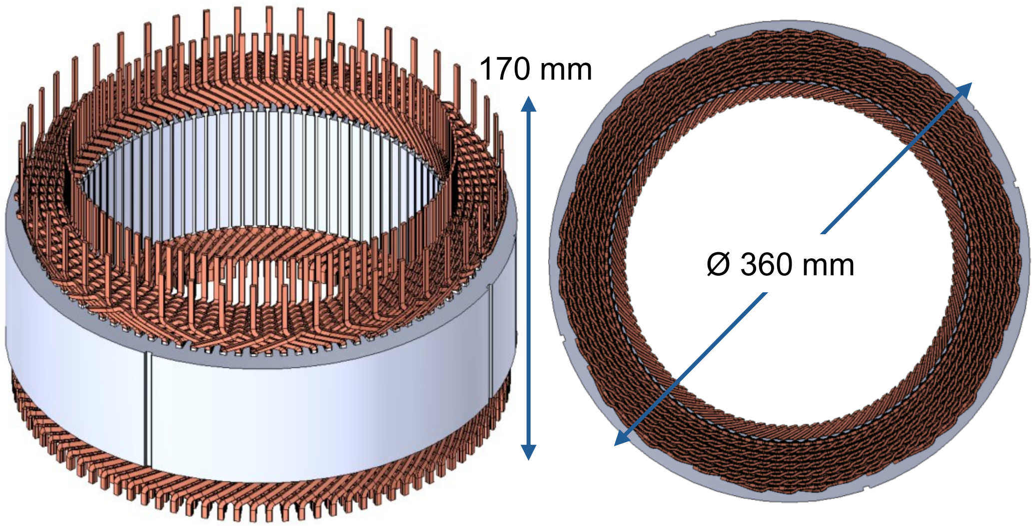


Parametric Modeling
Usage of the design algorithm for creating different tools regarding product variants

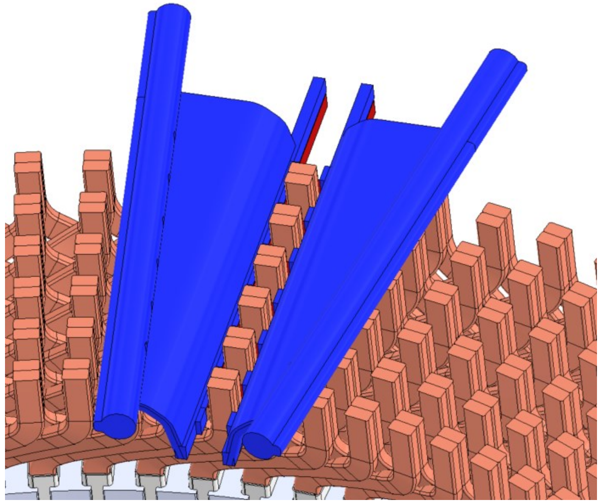


Automotive Stator
- 48 slots
- 4 hairpin pairs per slot
- 4 x 1.5 mm wire dimensions
- 192 welding joints





Truck Stator
- 96 slots
- 6 hairpin pairs per slot
- 4 x 2 mm wire dimensions
- 576 welding joints



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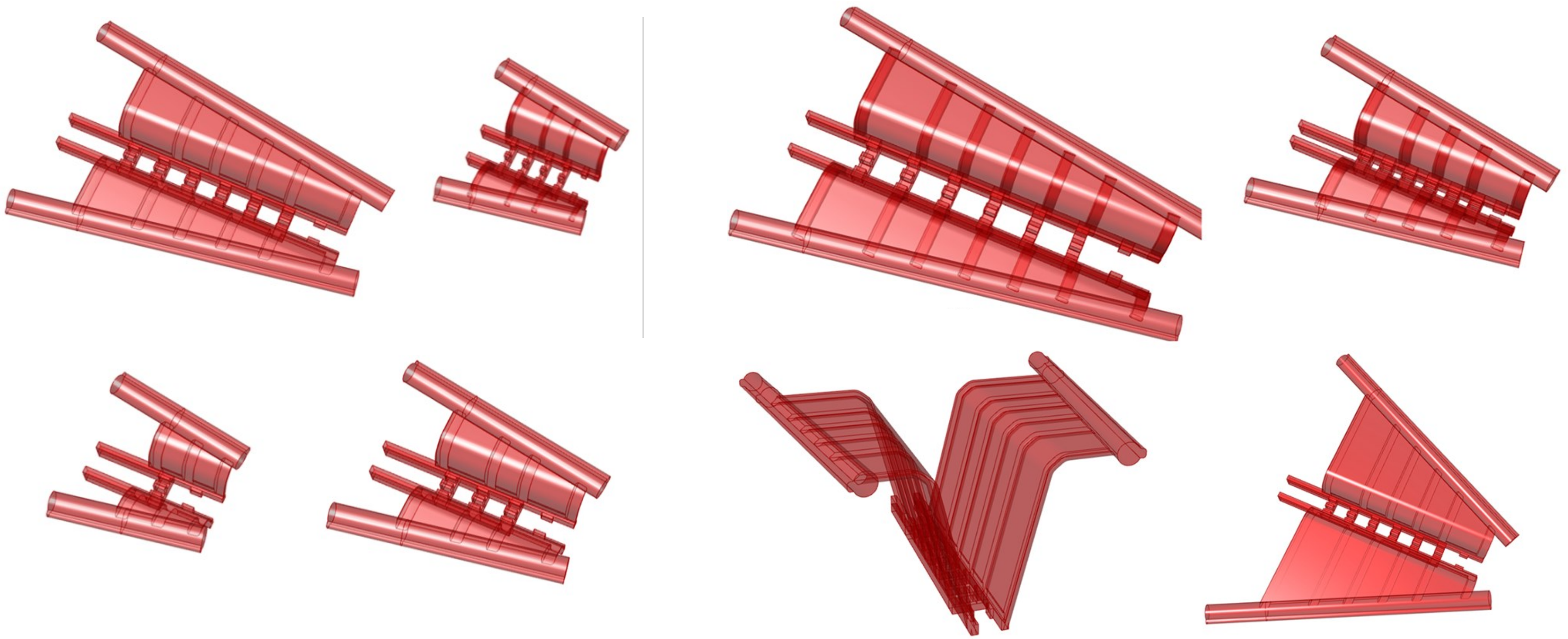
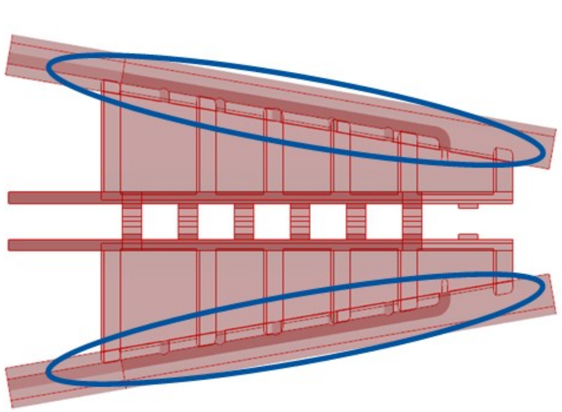
Design Algorithm
Automatically generated tool designs regarding varying input parameters

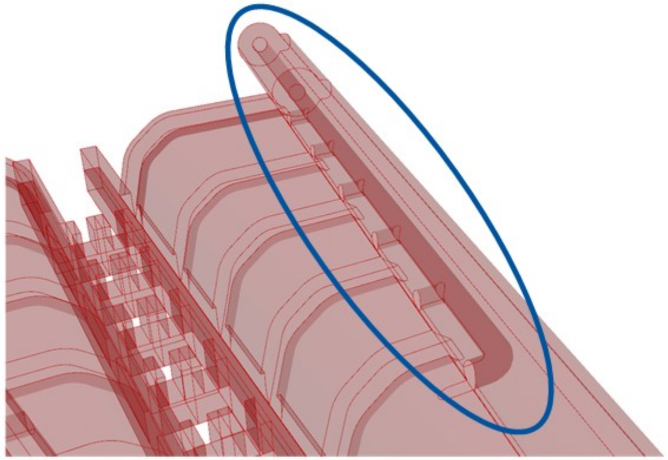


- Total of 42 input parameters allow to generate wide range of varying designs
- **Can adapt to variant**
  - Wire dimensions
  - Stator dimensions
  - number of hairpin per slot
  - Number of slots
  - Tolerance fields of the hairpin ends

  within seconds
- Implemented in Rhino3D® & Grasshopper® Plugin

Additive Tooling
Manufacturing of algorithm-aided tool designs and taking advantage of AM design potentials





- Integration of function
  - Fluid channel integration
  - Local shielding gas flow
  - Optimized welding results
- Additional function in design algorithm
- Selectable by boolean operator
- Production ready for LPBF

Further research

Extension on the whole hairpin production process chain and adaption to other products

With a consistent interface between production machines and tools the combination of parametric modeling and additive tooling is a solution to integrate variant flexibility to state of the art production lines

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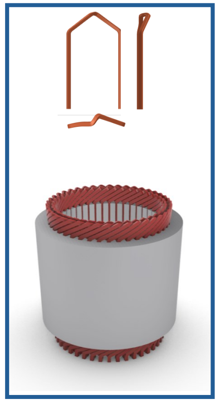

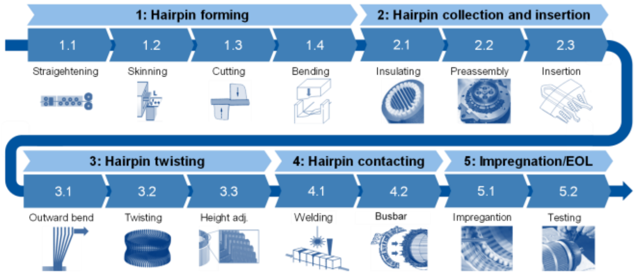

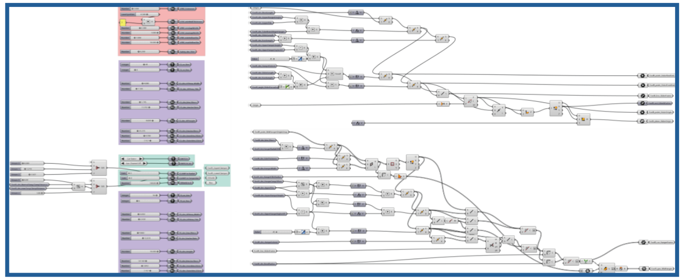

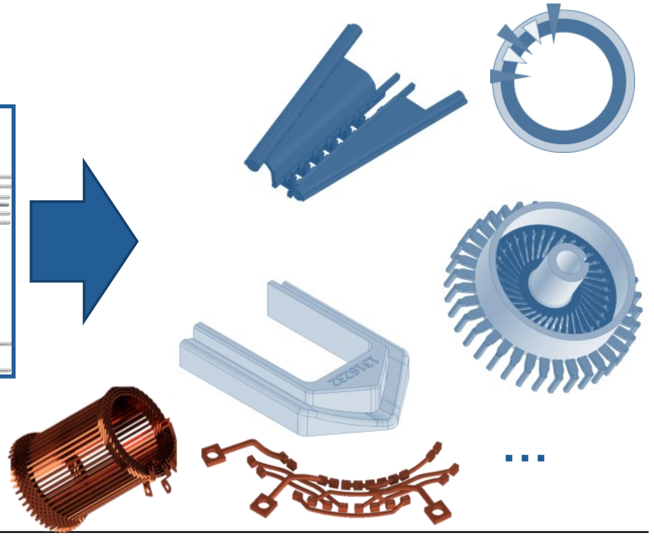

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Thank you for your attention

Carsten Putz
Your contact at DAP for Additive Manufacturing in the field of E-Mobility

Feel free to contact me:
carsten.putz@dap.rwth-aachen.de

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